

## ARTEMIS: The First Mission to the Lunar Libration Orbits

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### ABSTRACT

The ARTEMIS mission will be the first to navigate to and perform stationkeeping operations around the Earth-Moon L1 and L2 Lagrangian points. The NASA Goddard Space Flight Center (GSFC) has previous mission experience flying in the Sun-Earth L1 (SOHO, ACE, WIND, ISEE-3) and L2 regimes (WMAP) and have maintained these spacecraft in libration point orbits by performing regular orbit stationkeeping maneuvers. The ARTEMIS mission will build on these experiences, but stationkeeping in Earth-Moon libration orbits presents new challenges since the libration point orbit period is on the order of two weeks rather than six months. As a result, stationkeeping maneuvers to maintain the Lissajous orbit will need to be performed frequently, and the orbit determination solutions between maneuvers will need to be quite accurate.

The ARTEMIS mission is a collaborative effort between NASA GSFC, the University of California at Berkeley (UCB), and the Jet Propulsion Laboratory (JPL). The ARTEMIS mission is part of the THEMIS extended mission. ARTEMIS comprises two of the five THEMIS spacecraft that will be maneuvered from near-Earth orbits into lunar libration orbits using a sequence of designed orbital maneuvers and Moon & Earth gravity assists. In July 2009, a series of orbit-raising maneuvers began the proper orbit phasing of the two spacecraft for the first lunar flybys. Over subsequent months, additional propulsive maneuvers and gravity assists will be performed to move each spacecraft through the Sun-Earth weak stability regions and eventually into Earth-Moon libration point orbits.

We will present the overall orbit designs for the two ARTEMIS spacecraft and provide analysis results of the 3/4-body dynamics, and the sensitivities of the trajectory design to both maneuver errors and orbit determination errors. We will present results from the initial orbit-raising maneuvers.

### 1. INTRODUCTION

In May 2008, NASA's Heliophysics Senior Review panel approved the Acceleration Reconnection and Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission as part of the extended operations plan of the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission [1]. ARTEMIS will use simultaneous measurements of particles and electric and magnetic fields from two locations to provide the first three-dimensional information on how energetic particle acceleration takes place near the moon's orbit, in the distant magnetosphere, and in the solar wind. ARTEMIS will also collect unprecedented observations of the refilling of the space environment behind the dark side of the moon – the greatest known vacuum in the solar system – by the solar wind [2].

The THEMIS mission comprises five identical spacecraft each equipped with comprehensive packages of plasma and field instruments needed to determine the cause of geomagnetic substorms. THEMIS was launched onboard a Delta-II launch vehicle on February 17, 2007 from Cape Canaveral, Florida. The Mission Operations Center (MOC) at the University of California at Berkeley (UCB) provides spacecraft operations support for THEMIS. Tracking, telemetry, and command services are provided using the S-band frequency via various networks, including the Berkeley Ground Station (BGS), the Universal Space Network (USN), the NASA Ground Network (GN) and Space Network (SN).

THEMIS answered longstanding fundamental questions concerning the nature of the substorm instabilities that abruptly and explosively release solar wind energy stored within the Earth's magnetotail. The primary objectives of the mission were to 1) establish when and where substorms begin, 2) determine how the individual components of the substorm interact, 3) determine how substorms power the aurora, and 4) identify how local current disruption mechanisms couple to the more global substorm phenomena. THEMIS accomplished these tasks by employing 5 identically-instrumented spacecraft in carefully chosen orbits whose apogees line up once every 4 days over a dedicated array of ground observatories located in Canada and the northern United States. Three inner spacecraft ~10 Earth radii (RE) from Earth monitor current disruption onset, while two outer spacecraft at 20 and 30 RE remotely monitor plasma acceleration due to lobe flux dissipation. Magnetic field lines map phenomena occurring at the inner spacecraft to the ground arrays, where they can be observed as nightside auroral displays and geomagnetic perturbations.

The five THEMIS spacecraft were placed in highly elliptical orbits where the spacecraft would line up at apogee every four days. The apogee rotated slowly around the Earth-Sun line to cover the dayside, dawnside, nightside, and duskside of the magnetosphere. Initially, right after launch, the 5 THEMIS spacecraft were lined up in the same orbit with perigee & apogee altitudes of  $1.07 \times 15.4$  Earth radii (Re). Orbital maneuvers were performed to achieve the mission orbits. The THEMIS mission orbits relative to the geomagnetic tail are illustrated in Fig. 1. The mission orbit parameters, moving from the outermost to innermost spacecraft, are:

- \* Probe 1:  $1.3 \times 30$  Re
- \* Probe 2:  $1.2 \times 20$  Re
- \* Probes 3 and 4:  $1.5 \times 12$  Re
- \* Probe 5:  $1.5 \times 10$  Re

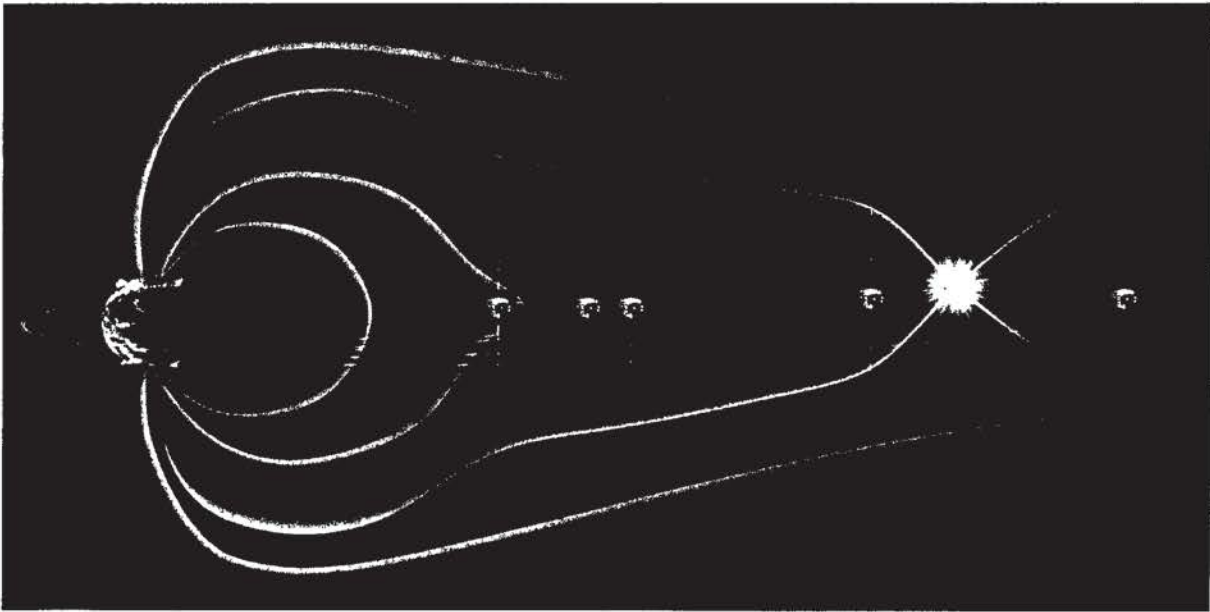


Fig. 1. THEMIS Constellation Configuration

The THEMIS team has achieved the primary science objectives of the THEMIS mission. The extended science mission will keep the three innermost THEMIS spacecraft in elliptical Earth orbits and maneuver the two outermost spacecraft to the lunar regime. The two outermost spacecraft are now designated as ARTEMIS probes P1 and P2. The THEMIS team had long known that substantial orbit maneuvers would be necessary for the P1 and P2 spacecraft to avoid entering a



deep umbral shadow that would drain all power from the batteries and put the spacecraft into a non-recoverable power state. At the request of the Principal Investigator (PI), analysts at the Jet Propulsion Laboratory (JPL) designed transfer trajectories for both P1 and P2 to insert them into Earth-Moon libration point orbits. The maneuver plan includes a series of propulsive Orbit-Raising Maneuvers (ORMs) to position each spacecraft for a series of lunar and Earth gravity assist maneuvers. The translunar orbit injections for P1 and P2 will occur in January and March 2010, respectively, with lunar libration point orbit captures in August and October 2010. After collecting science data in the Lissajous orbits for several months, the spacecrafts will maneuver into selenocentric orbits:

Each spacecraft is spin-stabilized with a nominal spin rate of roughly 20 RPM. Spacecraft attitude and rate are determined using telemetry from a sun sensor (SS), a three-axis magnetometer (TAM), and two single-axis inertial rate units (IRUs). The propulsion system on each spacecraft is a simple monopropellant hydrazine blow-down system. The propellant is stored in two equally sized tanks and either tank can provide propellant to any of the thrusters through a series of latch valves. Each observatory was launched with a dry mass of 77 kg and 49 kg of propellant, giving a wet mass of 126 kg at beginning of life.

Each spacecraft has four 4.4 Newton (N) thrusters – two axial thrusters and two tangential thrusters. The two tangential thrusters are mounted on one side of the spacecraft and the two axial thrusters are mounted on the lower deck, as shown in Fig. 2. The thrusters fire singly or in pairs – in continuous or pulsed mode – to provide orbit, attitude and spin rate control, as shown in Table 1. Orbit maneuvers can be performed by firing the axial thrusters in continuous mode, the tangential thrusters in pulsed mode, or a combination of the two (beta mode). Since there are no thrusters on the upper deck, the combined thrust vector is constrained to the lower hemisphere of the spacecraft.

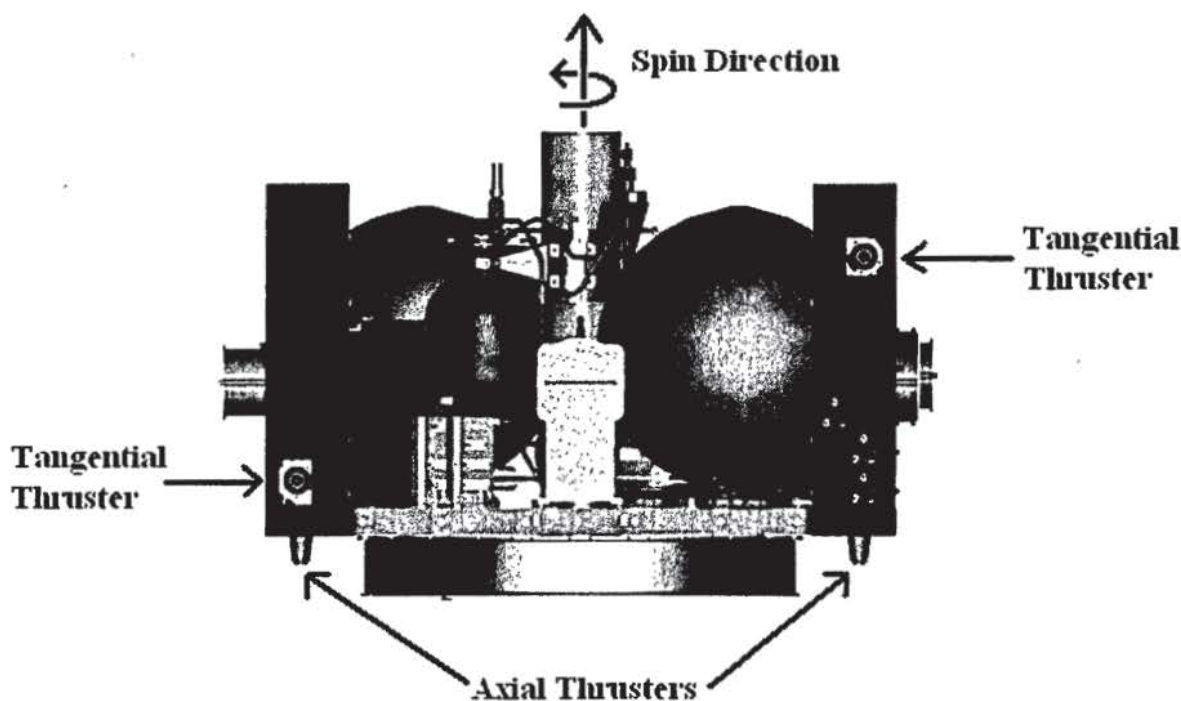











Fig. 2. Thruster Placements

Table 1. ARTEMIS Thruster Firing Modes

Thruster Firing Modes			
Maneuver Type	Thrusters Involved	Depiction of Operational Mode	Purpose of Maneuver
Axial Thrust	A1 and A2 continuous firing		Perigee or apogee change or combined in-plane and out-of-plane orbit change with stowed EFI booms
Side Thrust	T1 and T2 pulsed firing	 	Perigee or apogee change with deployed EFI booms
Beta Thrust	A1 and A2 continuous firing alternating with T1 and T2 pulsed firing	 	In-plane and out-of-plane orbit change with deployed EFI booms
Attitude Precession	A1 or A2 pulsed firing	 	Attitude change
Spin-up / Spin-down	T1 or T2 continuous or pulsed firing	 	Spin rate adjustment

## 2. ARTEMIS TRAJECTORY DESIGN

The ARTEMIS trajectory design is illustrated in Fig. 3 [3]. The two diagrams on the left show the ARTEMIS P1 and P2 trajectories in the Sun-Earth rotating frame during the translunar phase. This phase begins with a carefully planned series of Orbit-Raising Maneuvers (ORMs) performed near periapsis to methodically raise apoapsis to lunar distance. The ORMs are carefully timed to phase the final apoapsis approach with lunar approach to achieve a lunar gravity assist maneuver. Gravity assists are a key component of the ARTEMIS trajectory design, as neither spacecraft has sufficient propellant to perform a direct insertion into the lunar libration point orbits. During the last few orbits prior to the lunar encounter, small Lunar Targeting Maneuvers (LTMs) and Trajectory Correction Maneuvers (TCMs) will correct for any maneuver execution errors during the last ORMs and align the lunar approach trajectory to the proper B-plane targets. Table 2 shows the total delta-v budget and margin for each spacecraft.

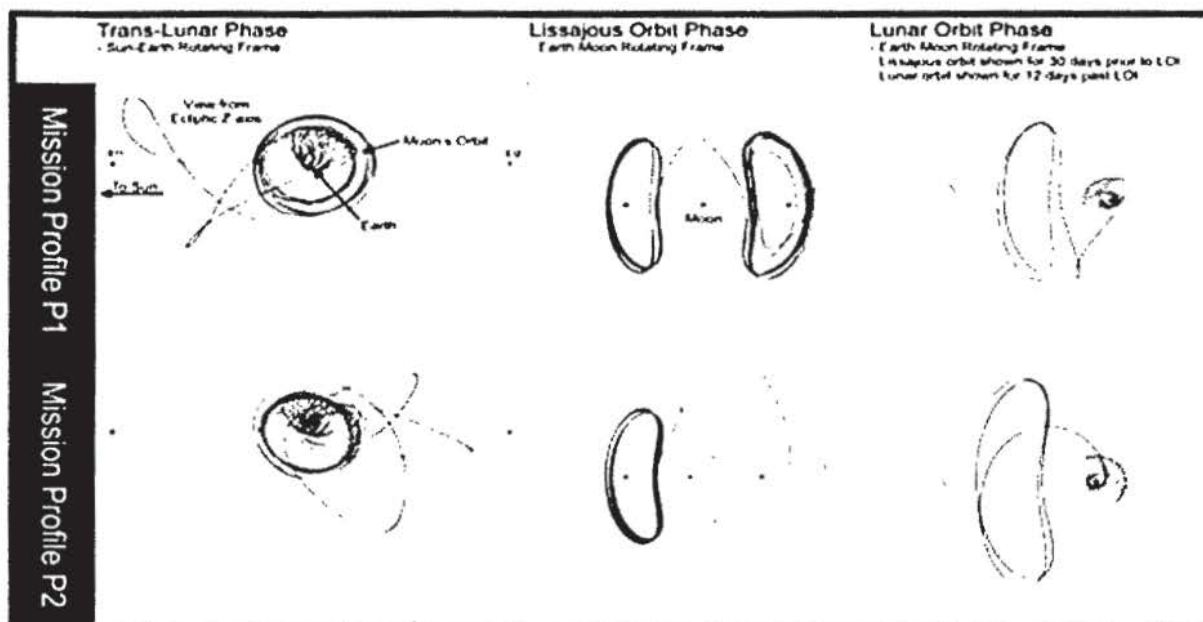


Fig. 3. ARTEMIS Trajectory Design

Table 2. ARTEMIS Delta-V Budget

	P1 Cost (m/s)	P2 Cost (m/s)
Orbit Raising Maneuvers (ORMs)	103.2	233.9
Flyby Targeting Maneuvers (FTMs)	6.9	11.4
Deep Space Maneuvers (DSMs)	4.8	29.1
Lissajous Trajectory Insertion (LTI)	0.8	1.5
Lunar Orbit Insertion (LOI)	89.9	117.1
Deterministic $\Delta V$ Total	205.7	392.8
Sources of additional $\Delta V$ cost:		
TLI declination penalty	(included)	(included)
TLI gravity and steering losses (with shadow)	(included)	(included)
LOI declination penalty	2	2
LOI gravity and steering losses	(included)	(included)
Lissajous maintenance	15	12
Trajectory Correction Maneuvers (TCMs), assumed as 4% of total budget	9	17
Total $\Delta V$	232	424
Available $\Delta V$	335	457
Margin	94	33
Liens Against Margin:		
Matching ORM phase to transfer phase	(none)	(none)
Precession corrections during ORM phase	1	(included)
Lissajous maintenance increase	5	4
End of mission deorbit	10?	10/64

## 2.1 Orbit Raising Maneuver (ORM) Phase

Tables 3 and 4 provide the finite maneuver plan summary information for the P1 and P2 spacecraft, respectively. Since the initial apogee altitude, prior to the orbit raising maneuvers, is 30 RE for P1 and only 20 RE for P2, many more ORM maneuvers are required for P2. There are a total of 5 ORM plus 3 FTMs for P1 and 27 ORM plus 1 FTM for P2. Both ARTEMIS spacecraft have an operational constraint that propulsive maneuvers cannot be performed while the spacecraft is in the Earth's umbral shadow. Since umbra frequently occurs near the perigee point, many of the



ORM maneuvers are divided into an "A" segment that is completed just prior to entering shadow and a "B" segment that is performed just after exiting from shadow.

Table 3. ARTEMIS P1 ORM Finite Burn Summary

Maneuver	Burn Start Time (UTC)	Burn Stop Time (UTC)	Duration (s)	$\Delta V$ (m/s)	Fuel Used (kg)	Remaining Fuel (kg)
ORM 01-A	2009-08-01 19:40:54	2009-08-01 19:40:54	1212.1	8.22	0.34	14.21
ORM 01-B	2009-08-01 20:30:41	2009-08-01 20:30:41	1244.4	8.42	0.35	13.86
ORM 02-A	2009-08-10 13:04:36	2009-08-10 13:04:36	1255.8	8.42	0.35	13.51
ORM 02-B	2009-08-10 13:54:42	2009-08-10 13:54:42	1270.3	8.50	0.35	13.09
ORM 03-A	2009-08-20 07:39:57	2009-08-20 07:39:57	1039.6	6.94	0.29	12.80
ORM 03-B	2009-08-20 08:27:36	2009-08-20 08:54:46	1629.8	10.79	0.44	12.36
ORM 04-A	2009-08-31 10:44:10	2009-08-31 11:14:30	1819.7	11.96	0.49	11.87
ORM 04-B	2009-08-31 11:47:41	2009-08-31 12:23:07	2125.5	13.86	0.57	11.30
ORM 05-A	2009-09-13 23:01:01	2009-09-13 23:32:50	1909.3	12.40	0.51	10.79
ORM 05-B	2009-09-14 00:07:29	2009-09-14 00:25:02	1053.4	6.85	0.28	10.52
FTM 1	2009-10-12 12:25:19	2009-10-12 12:27:38	139.0	0.87	0.04	10.48
FTM 2	2009-11-22 05:01:21	2009-11-22 05:02:18	57.4	0.36	0.01	10.47
FTM 3	2009-12-02 07:13:49	2009-12-02 07:28:29	879.9	5.69	0.23	10.24

Table 4. ARTEMIS P2 ORM Finite Burn Summary

Maneuver	Burn Start Time (UTC)	Burn Stop Time (UTC)	Duration (s)	$\Delta V$ (m/s)	Fuel Used (kg)	Remaining Fuel (kg)
ORM 01	2009-07-21 07:07:06	2009-07-21 07:31:54	1489.0	10.67	0.48	21.14
ORM 02	2009-07-25 10:22:54	2009-07-25 10:35:29	754.1	5.27	0.24	20.66
ORM 03-A	2009-07-29 15:07:30	2009-07-29 15:13:21	351.0	2.41	0.11	20.43
ORM 03-B	2009-07-29 15:45:01	2009-07-29 16:14:19	1757.6	8.37	0.36	20.32
ORM 04-A	2009-08-03 00:34:50	2009-08-03 00:46:33	703.7	3.30	0.14	19.95
ORM 04-B	2009-08-03 01:16:52	2009-08-03 01:47:42	1849.2	8.74	0.38	19.81
ORM 05-A	2009-08-07 15:08:11	2009-08-07 15:21:59	827.8	3.86	0.17	19.43
ORM 05-B	2009-08-07 15:52:06	2009-08-07 16:20:15	1689.0	7.92	0.34	19.26
ORM 06-A	2009-08-12 11:09:39	2009-08-12 11:22:15	756.2	3.51	0.15	18.89
ORM 06-B	2009-08-12 11:52:15	2009-08-12 12:22:30	1814.9	8.48	0.37	18.74
ORM 07-A	2009-08-17 12:52:08	2009-08-17 13:02:01	592.2	2.72	0.12	18.38
ORM 07-B	2009-08-17 13:33:38	2009-08-17 14:00:46	1627.9	7.56	0.32	18.26
ORM 08-A	2009-08-22 20:14:35	2009-08-22 20:25:50	674.8	3.08	0.13	17.93
ORM 08-B	2009-08-22 20:56:27	2009-08-22 21:23:18	1611.0	7.43	0.32	17.80
ORM 09-A	2009-08-28 09:24:23	2009-08-28 09:34:31	607.0	2.76	0.12	17.49
ORM 09-B	2009-08-28 10:05:46	2009-08-28 10:27:10	1284.4	5.88	0.25	17.37
ORM 10-A	2009-09-03 03:56:43	2009-09-03 04:09:52	789.0	3.58	0.15	17.12
ORM 10-B	2009-09-03 04:40:48	2009-09-03 05:01:08	1240.2	5.65	0.24	16.97
ORM 11-A	2009-09-09 04:45:05	2009-09-09 04:59:23	857.6	3.88	0.16	16.72
ORM 11-B	2009-09-09 05:30:23	2009-09-09 05:47:18	1014.8	4.59	0.19	16.56
ORM 12-A	2009-09-15 11:28:29	2009-09-15 11:41:42	973.2	4.39	0.19	16.37
ORM 12-B	2009-09-15 12:15:38	2009-09-15 12:30:36	896.9	4.03	0.17	16.18
ORM 13-A	2009-09-22 01:16:15	2009-09-22 01:33:53	1058.4	4.76	0.20	16.01
ORM 13-B	2009-09-22 02:04:56	2009-09-22 02:18:31	815.7	3.65	0.15	15.81
ORM 14-A	2009-09-28 21:33:30	2009-09-28 21:55:14	1304.8	5.86	0.25	15.65
ORM 14-B	2009-09-28 22:27:03	2009-09-28 22:40:14	790.8	3.52	0.15	15.41
ORM 15	2009-10-06 02:42:19	2009-10-06 03:00:37	1098.5	4.91	0.21	15.26
ORM 16	2009-10-13 12:26:06	2009-10-13 12:46:56	1250.6	8.20	0.35	15.05
ORM 17	2009-10-21 08:06:13	2009-10-21 08:31:35	1522.6	9.96	0.43	14.70
ORM 18	2009-10-29 14:51:55	2009-10-29 15:18:38	1603.0	10.45	0.45	14.27
ORM 19	2009-11-07 11:16:24	2009-11-07 11:43:24	1620.1	10.52	0.45	13.82
ORM 20	2009-11-16 22:38:18	2009-11-16 23:04:56	1598.5	10.34	0.44	13.37
ORM 21	2009-11-27 02:15:00	2009-11-27 02:25:37	636.9	4.06	0.17	12.92
ORM 22	2009-12-07 12:45:39	2009-12-07 12:51:22	343.2	2.17	0.09	12.75
ORM 23	2009-12-18 07:35:03	2009-12-18 07:47:22	739.3	4.72	0.20	12.66
ORM 24	2009-12-29 11:30:12	2009-12-29 11:46:31	978.4	6.25	0.27	12.46
ORM 25	2010-01-10 05:02:15	2010-01-10 05:22:02	1186.8	7.59	0.32	12.19
ORM 26	2010-01-22 19:02:23	2010-01-22 19:18:44	981.2	6.24	0.26	11.87
ORM 27	2010-02-26 08:02:55	2010-02-26 08:33:05	1809.2	11.55	0.49	11.61
FTM 1	2010-03-24 17:50:13	2010-03-24 18:19:52	1778.7	11.39	0.48	11.12

## 2.1 Translunar Phase

Following the first lunar swingby, the P1 spacecraft flies under the Earth and performs a second lunar swingby roughly 13 days later, as shown in the Sun-Earth rotating frame in Fig. 4. The first of two deep space maneuvers (DSM 1) is performed 33 days later. The first DSM targets the Earth's B-plane for an Earth gravity assist maneuver. Following the Earth swingby, the P1 spacecraft flies into the general vicinity of the Sun-Earth L1 Lagrangian point. This region is referred to as the "weak stability boundary" region. At the final bend in the P1 trajectory, the spacecraft is at a maximum range of 1.50 million km from the Earth. At this point, the trajectory begins to fall back towards the Earth-Moon system. A second deep space maneuver (DSM 2) targets the Earth-Moon L2 Lagrangian point. A large Lissajous Insertion Orbit (LOI) maneuver will be performed to insert P1 into the proper L2 Lissajous orbit.



The P2 translunar trajectory, shown in Fig. 5, is less complex. There is a single lunar swingby and a single deep space maneuver, then two Earth gravity assists and the Lissajous orbit insertion maneuver. For both P1 and P2, we have allocated 4% of the total propellant budget to perform any required trajectory correction maneuvers (TCMs) along the way.

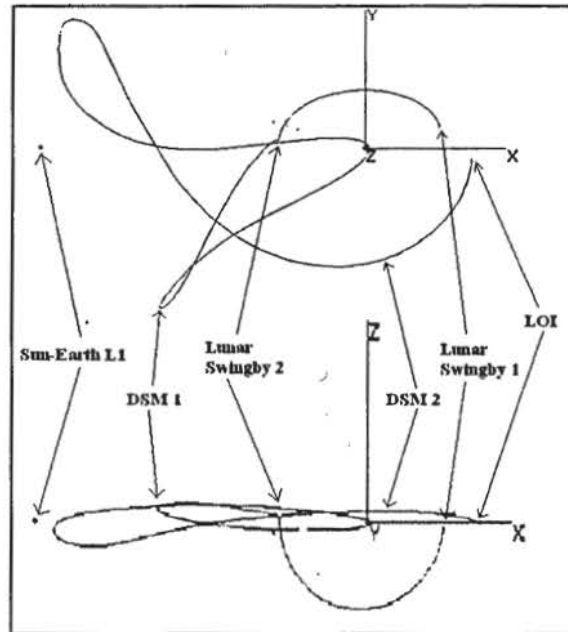


Fig. 4. ARTEMIS P1 Translunar Trajectory Design

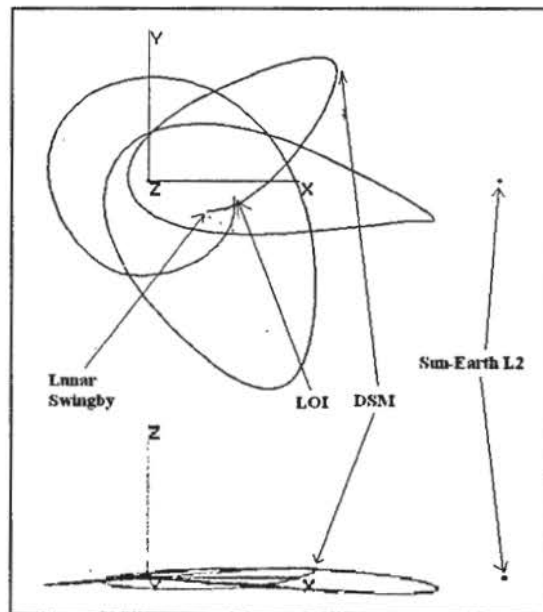


Fig. 5. ARTEMIS P2 Translunar Trajectory Design

### 2.3 Lissajous Phase

The many months that the ARTEMIS team spends performing orbit raising maneuvers, lunar gravity assists, Earth gravity assists, and deep space maneuvers are all a prelude to the ultimate goal of reaching the lunar Lissajous orbits. The ARTEMIS science mission begins once each spacecraft is inserted into its Lissajous orbit. Since L1 and L2 are unstable Lagrangian points, the operations team must perform frequent stationkeeping maneuvers to maintain each spacecraft in



the Lissajous orbits for several months. We will be the first mission to perform lunar Lissajous stationkeeping maneuvers, and that present us with new challenges. We will draw upon mission experience from NASA GSFC in performing stationkeeping maneuvers at Sun-Earth L1 (WIND, ISEE-3, SOHO & ACE missions) and at Sun-Earth L2 (WMAP and future mission JWST).

The Lissajous orbits for the two ARTEMIS spacecraft are illustrated in Fig. 6. The baseline trajectory for the P1 satellite places it into an L2 Lissajous orbit on August 23, 2010. Stationkeeping maneuvers will be performed to maintain P1 in the L2 orbit for 131 days. Then, a small maneuver will be performed to move P1 to the L1 orbit and it will be maintained there for 85 days. The baseline trajectory for spacecraft P2 inserts it near the L2 point on October 2, 2010. P2 flies past the L2 point and is captured into an L1 Lissajous orbit on October 10<sup>th</sup> and it remains there for 154 days. The trajectory design of the ARTEMIS constellation allows for science data to be collected for several weeks with the two spacecraft on opposing sides of the moon and with both spacecraft on the near side of the moon. At the conclusion of the Lissajous mission phase, each ARTEMIS spacecraft will perform a large maneuver to leave its Lissajous orbit and be captured into a selenocentric orbit.

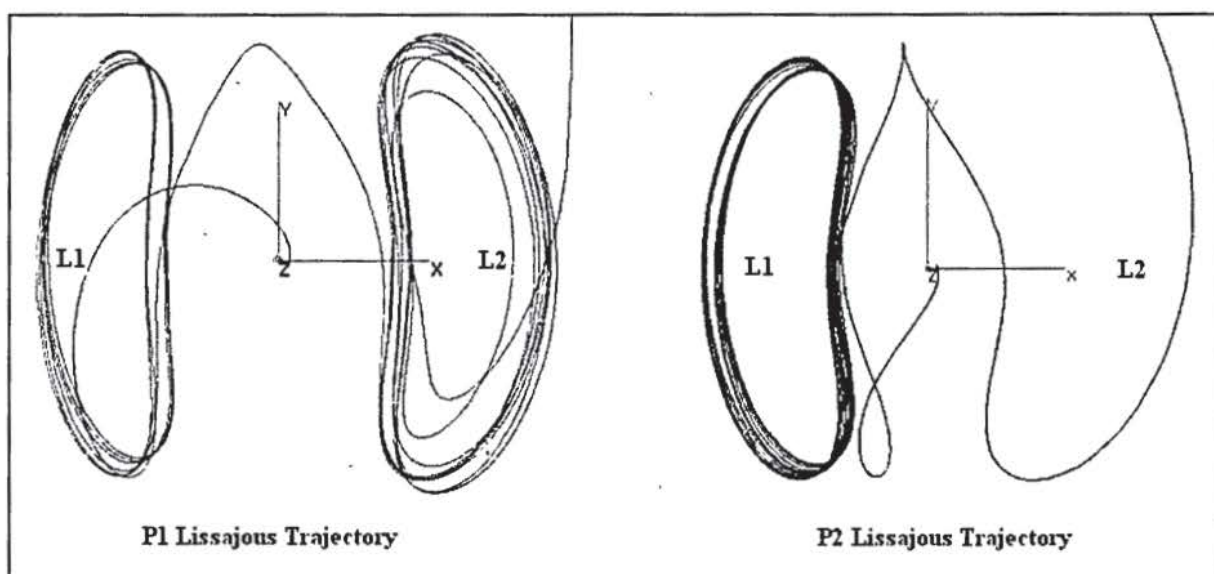


Fig. 6. ARTEMIS Lissajous Trajectory Design

Experience from WIND, ISEE-3, SOHO, ACE, WMAP, and JWST provide us with insight into key maneuver planning parameters. The first key parameter is the required accuracy of pre-maneuver orbit determination solutions. Experience from past missions indicates that orbit knowledge ( $3\text{-}\sigma$  RSS) should be better than 1 km in position and 1 cm/s in velocity. That is the current baseline for the ARTEMIS mission. We will achieve those accuracies by collecting long data arcs of both range and Doppler TRK-2-34 tracking data and processing it in the Goddard Trajectory Determination System (GTDS). All spacecraft tracking, telemetry, and command services in the lunar libration point region come from the three ground stations of the NASA Deep Space Network (DSN) using their 34-m antennas. The GTDS orbit solution becomes the first input into the maneuver planning process.

Another key parameter in performing Lissajous stationkeeping maneuvers is at which point in the orbit and in which direction to apply the delta-v. These parameters are best understood in the rotating libration point (RLP) reference frame [5]. The RLP is a Cartesian orthogonal frame, illustrated in Fig. 7 and defined as:

- the primary is the heavier of the two bodies, the secondary as the lighter body (For the ARTEMIS mission, the Earth is the primary and the Moon is the secondary body)
- the x-axis is in the direction pointing from the primary body to the secondary body
- the y-axis is orthogonal to the x-axis in the plane of the secondary's motion about the primary, pointing in the direction the secondary moves about the primary
- the z-axis is orthogonal to the x and y axes, in a right-hand sense
- the origin is at a convenient point (for ARTEMIS, either the L1 or L2 Lagrange point)

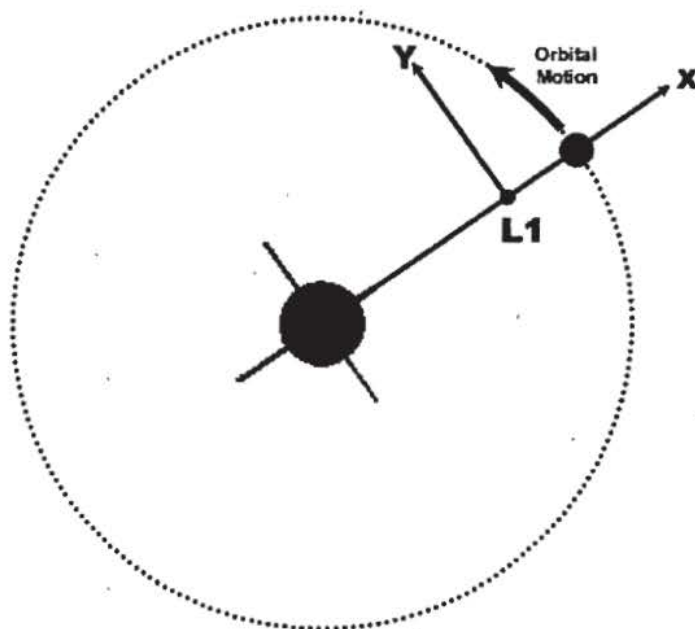


Fig. 7. Rotating Libration Point Reference Frame

Using the RLP coordinate system, we can define stationkeeping strategies in terms of  $\{X, Y, Z\}$  components for maneuver placement and direction. Previous libration point orbit missions (SOHO, ACE, WMAP) have used a strategy of performing stationkeeping burns when the spacecraft crosses the RLP X-Z plane and maneuvering in a direction to target a zero X velocity at the next X-Z plane crossing. For future libration point missions, including JWST and ARTEMIS, we are considering a “bisection” method. With this approach we will target the same constraint – of crossing the X-Z plane with a zero X velocity – but we will propagate the orbit for as long as 1.5 revs before we apply the constraint. The advantages to this targeting approach for ARTEMIS are twofold. First, we allow the natural orbit dynamics to drive the motion of the spacecraft for a longer period of time instead of “forcing” a target constraint to be met in one-half revolution. Second, since the libration point orbit revolution cycle is much shorter for an Earth-Moon system than for a Sun-Earth system (roughly two weeks vs. six months), we can use longer tracking arcs for more accurate orbit determination if we maneuver less frequently.

## 2.4 Lunar Phase

At the completion of the Lissajous orbit phase, the ARTEMIS satellites will perform large orbit maneuvers to depart the lunar libration point orbits and be captured into selenocentric orbits. The total magnitude of the delta-v maneuvers will be 89.9 m/s for P1 and 117.1 m/s for P2. Since each ARTEMIS spacecraft will have depleted much of its fuel and will have low tank pressure, this delta-v cannot be achieved in a single burn. We plan to use six burns for P1 and ten burns for P2 to



achieve the total delta-v. P1 will be in a retrograde orbit and P2 will be in a posigrade orbit to maximize science spatial observations. Fig. 8 shows the relative spacecraft motions for the first 90 days in lunar orbit. The satellites will remain in lunar orbit for 18 months, after which time the ARTEMIS science mission is complete. The end of mission maneuvers will be a controlled hard entry to the lunar surface.

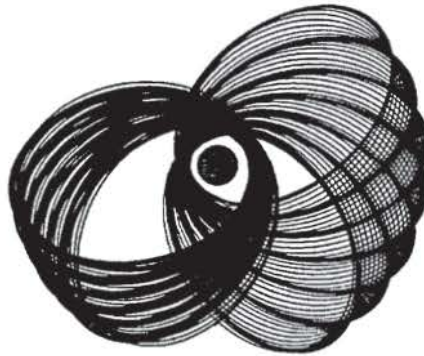


Fig. 8. ARTEMIS Lunar Orbits, First 90 Days

### 3. FINITE MANEUVER PLANNING PROCESS

NASA personnel used a variety of Commercial Off-The-Shelf (COTS) and Government Off-The-Shelf (GOTS) software to develop the baseline trajectory plans. The tools included LTOOL, Mystic, MONTE, CATO, STK/Astrogator, GMAT, and ODTBX. UCB uses the Goddard Maneuver (GMAN) software to plan each finite burn. The maneuver planning and execution process is illustrated in Fig. 9.

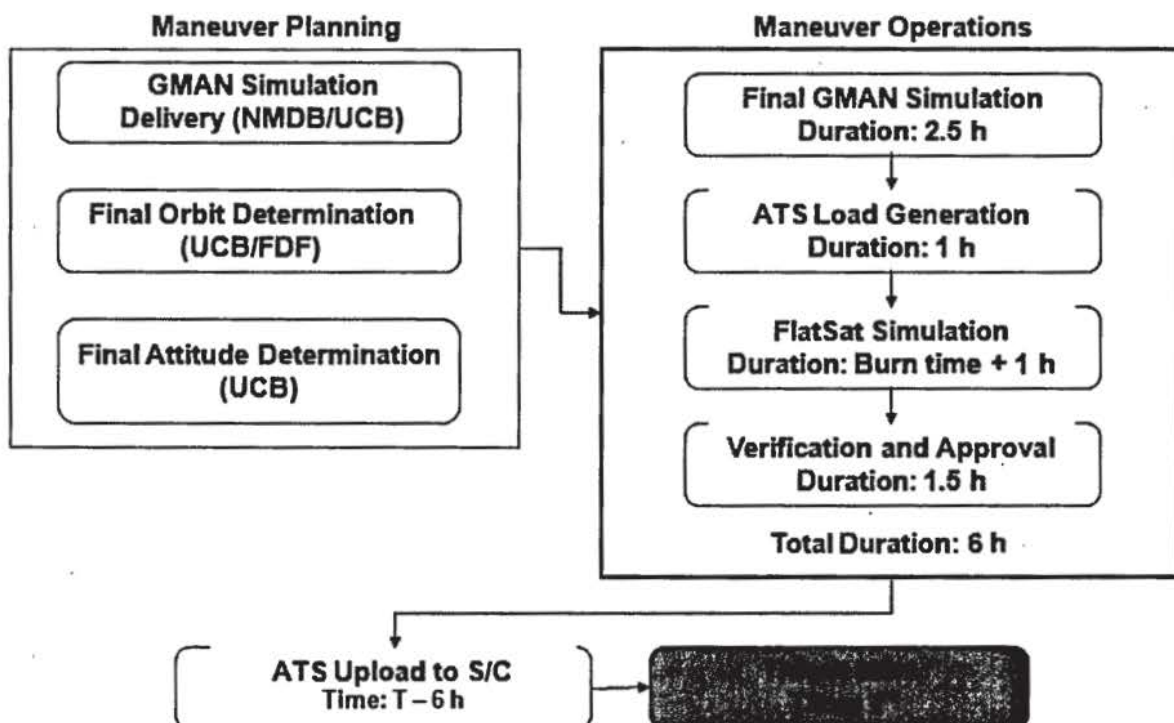


Fig. 9. Maneuver Planning & Execution Process

#### 4. FINITE MANEUVER PERFORMANCE

To date, several orbit raising maneuvers have been performed for both the P1 and P2 spacecraft. After each maneuver (or paired sets of maneuvers), the MOC schedules several tracking data passes from the ground stations and processes this data to provide a post-burn orbit solution. The post-burn orbit knowledge allows the MOC to calibrate the performance of each maneuver set and determine whether each maneuver was a bit "hot" or "cold". The performance to date is shown in Table 5. Any performance errors are corrected during the next ORM by retargeting the upcoming maneuver(s) given the post-burn orbit knowledge.

Table 5. Planned & Actual Finite Burn Performance

Spacecraft	Maneuver	$\Delta V$ (m/s)		Performance
		Planned	Actual	Actual vs. Planned
P1	ORM 01	16.55	16.35	(-1.208%)
P1	ORM 02	17.50	17.60	+0.571%
P2	ORM 01	10.73	11.12	+3.635%
P2	ORM 02	4.38	4.41	+0.685%
P2	ORM 03	11.40	11.46	+0.526%
P2	ORM 04	11.81	11.98	+1.439%
P2	ORM 05	11.50	11.67	+1.478%
P2	ORM 06	10.83	10.84	+0.092%

#### 5. ORBIT DETERMINATION

The GN stations provide range and Doppler tracking data in the Universal Tracking Data Format (UTDF). The DSN stations provide range and range rate data in TRK-2-34 format. The MOC converts the TRK-2-34 format to UTDF format. All UTDF files are then converted to 60-byte format for usage with GTDS. GTDS uses a batch least squares algorithm to estimate the orbit from the tracking observations. These orbit solutions are used to calibrate the performance of each maneuver and to enable planning for future maneuvers.

#### 6. CONCLUSIONS

The two ARTEMIS spacecraft are well on their way to Lissajous orbit insertion at the Earth-Moon L2 and L1 Lagrangian points, respectively, in August and October 2010. The team has developed an orbit raising maneuver sequence and a translunar maneuver sequence to reach the Lissajous insertion points. We have developed strategies for orbit stationkeeping around the lunar libration points, a plan for transfer into selenocentric orbit at the end of the Lissajous phase, and an end of mission plan. The team has designed trajectories that meet the spacecraft propellant budgets with margin. The planned trajectories will allow for new and exciting measurements of the geomagnetic fields in the lunar regime. ARTEMIS will be a pathfinder for future missions operating in the lunar libration point regions and will provide unprecedented science observations of the magnetosphere in selected lunar regimes.

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